

Analysis and Improvement of Performance Characteristics of a Proportional Hydraulic Valve

Fakhredin Bayat^{*1}, Alireza Fadaie Tehrani², Mohammad Danesh³

Department of Mechanical Engineering, Isfahan University of Technology
Isfahan 84156-83111, Iran

^{*1}f.bayat65@yahoo.com; ²mcjaft@cc.iut.ac.ir; ³danesh@cc.iut.ac.ir

Abstract

Increasing use of hydraulic control valves (HCVs) in industry has led to development of a high potential research area for studying them. Applied magnetic materials in proportional solenoids (PSs) of HCVs have remarkable effects on magnetic force. The main idea of this paper is to investigate the effects of different magnetic materials used in the PS's core and plunger, on the dynamic behavior of the PS and to obtain their importance levels. This helps to choose the proper materials that improve the performance characteristics of the PS. Different combinations of magnetic materials with their non-linear B-H curves have been applied in ANSYS software package to determine the magnetic behaviors (magnetic force, magnetic flux density) of the materials. Magnetic force-displacement curves are obtained for the different combinations of the materials by finite element analysis (FEA), based on them the dynamic behavior of the PS can be studied without constructing a physical prototype. The Magnetic flux density and force are also calculated using finite element method (FEM) and the results have been compared with the experimental results obtained from an actual PS.

Keywords

Proportional Solenoid; Finite Element Analysis; Magnetic Field Density; Optimal Design; Hydraulic Control Valve

Introduction

To examine and develop the performance characteristics of PSs in HCVs, many investigations have been done in recent years. Some of these investigations are based on the magnetic characteristics to achieve the most exact control of HCV. Different dimensional characteristics were analyzed by the FEM and the obtained results were compared with experimental results, and finally a new design with the improved characteristics was proposed. The FEM program was acceptable because the values of magnetic flux density were computed by the FEM agreed with the measured values [1, 2 and 3].

In other researches, the effects of various materials on force versus position characteristics of solenoid valves were investigated by the FEA and the simulating results were confirmed with experiment results [4, 5]. Also, a new research has been done by using a multi-physics FEM of a solenoid valve that is able to make predictions of the stresses, strains and temperatures within the solenoid valve [6]. The different soft magnetic materials that are shown in Table 1 have been used to investigate the driving force on the plunger. The effects of the non-linear B-H curves of these materials on the performance of PS have been investigated, too. The experimental data used in the following sections belongs to the HCV shown in Fig. 1. The considered portion for modeling and simulating in ANSYS has been shown in the following figure.

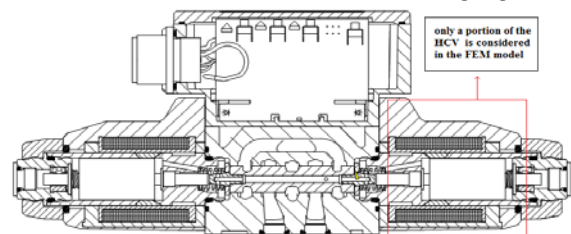


FIG. 1 A SCHEMATIC OF THE HCV AND CONSIDERED PORTION FOR MODELING AND SIMULATING

The organization of the rest of this paper is as follows; in section 1, a finite element model to simulate the PS and two different methods for calculating the magnetic force have been presented. In section 2, the magnetic flux density and distribution of flux lines for actual material in a specified position of plunger have been shown. The simulation results have been validated by experimental results in this section. In section 3, to achieve the optimal design, different materials with different conditions of simulation have been examined and their results have been illustrated. Finally, concluding remarks have been presented in final section.

Magnetic Field Simulation

A two-dimensional (2D) axisymmetric model for modeling the PS in ANSYS software package is used. The element of PLANE53 is used for meshing the model. This element models 2D axisymmetric magnetic field and is defined by eight nodes and has up to four degrees of freedom per node. Half of core with its surrounding air is meshed and mirrored to form the whole core. After defining the material specifications, loading and boundary conditions, the HCV's magnetic specifications such as magnetic field and force can be calculated non-linearly by ANSYS. A meshed model of PS in electromagnetic analysis (EMA) is shown in Fig. 2.

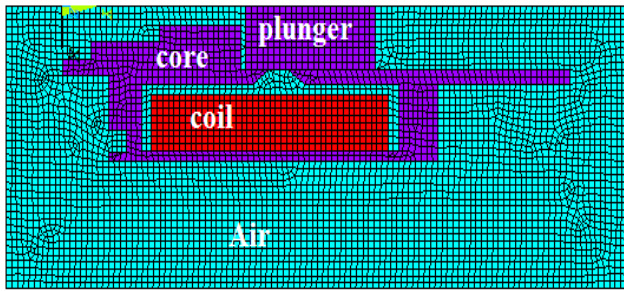


FIG.2 A MESHED MODEL OF PROPORTIONAL SOLENOID

Different methods have been used to calculate the magnetic force [7, 8]. Two methods are used in ANSYS to calculate the magnetic force, the Maxwell stress tensor and the virtual work methods. The Maxwell stress tensor provides a convenient way of computing forces acting on the plunger by evaluating a surface integral. The equation of force by this method is presented as follows;

$$F = \iint_S \bar{T} \cdot d\mathbf{s} \quad (1)$$

where F is the magnetic force on the surface of the plunger (S) and is $\bar{T}$ the stress tensor as dyadic form. This equation is derived from the following Maxwell equations.

$$\nabla \times \{H\} = \{J\} \quad (2)$$

$$\{B\} = \mu \cdot \{H\} \quad (3)$$

$$\nabla \cdot \{B\} = 0 \quad (4)$$

where $\{H\}$ is magnetic field intensity, $\{J\}$ is current density, $\{B\}$ is magnetic flux density and μ is permeability of material. Another approach to calculate the magnetic force is virtual work method. Although, the Maxwell stress tensor provides a convenient approach for computing forces, however, the virtual work method is best suited, since it is less dependent on the mesh size and shape than Maxwell stress tensor method [9].

The force on the plunger by virtual work principle is given by Eq. (6). This equation has been derived based on constant coil current assumption.

$$F = \lim_{\Delta x \rightarrow 0} \frac{\Delta W'}{\Delta x} = \frac{dW'}{dx} = - \left[\left(\frac{E_{x+\Delta x} + E_x}{\Delta x} \right) \right] \quad (5)$$

where F is the force on the plunger and dx is the virtual displacement of the plunger. ΔW is incidental energy change on the very small displacement Δx .

E_x is co-energy at zero displacement and $E_{x+\Delta x}$ is the co-energy at the assumed plunger position. The non-linear B-H curve of the material used in the experimental method to derive the magnetic force is shown in Fig. 3.

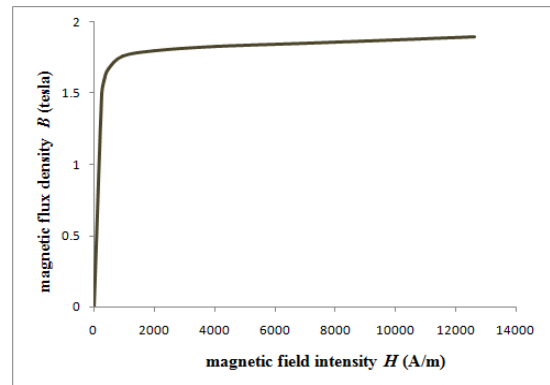


FIG.3 A NON-LINEAR B-H CURVE OF THE USED MATERIAL

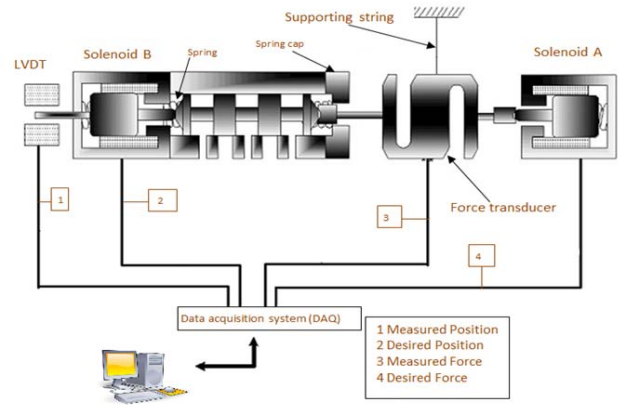


FIG.4 EXPERIMENTAL SETUP FOR ACQUIRING DATA

Experimental Results

The experimental procedure has been depicted in Fig. 4. Force output tests with currents rising up to the maximum operating value are carried out for 10 different armature positions over the 5mm stroke length. The solenoid B under test was heated to the required temperature prior to each experiment by passing a constant current through the coil. An LVDT integral to the valve was used to measure the displacement of the spool, while a force transducer was used to measure the change in force due to

Solenoid B. All test results described in this paper are from tests carried out with the solenoid coil at 50°C. The D.C step voltage used in this case was 15V, selected to give a final current of 1A in the resistance of the solenoid at that temperature.

The calibrations of the amplifiers, force and position transducer are not explained in this article. A data acquisition system (DAQ) with 12-bit resolution is used for all experiments. In Fig. 5, routes of 2 and 4 are correcting routes in the setup. By applying voltage on solenoid B, magnetic force has been obtained by force transducer in the route3. Simultaneous by acquiring force, the displacement of solenoid is acquired by the route 1. Finally, comparison between simulation and experimental data is shown in Fig. 5. Simulation data are satisfactory and validated by experiment data.

The magnetic flux diagram and contour graph of magnetic flux density for the current of 1A in the 3mm position of the plunger are shown in Fig. 6 and Fig. 7, respectively.

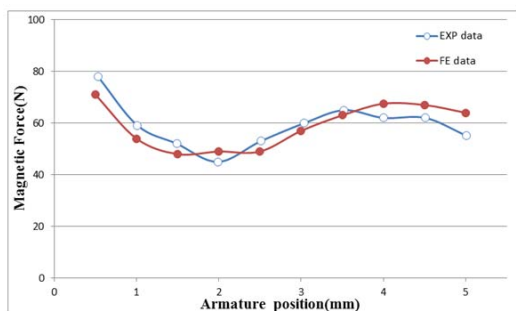


FIG.5 COMPARISON BETWEEN EXPERIMENTAL AND SIMULATION RESULTS

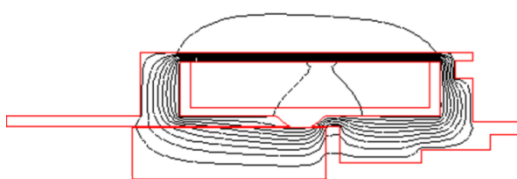


FIG.6 DISTRIBUTION OF MAGNETIC FLUX LINES

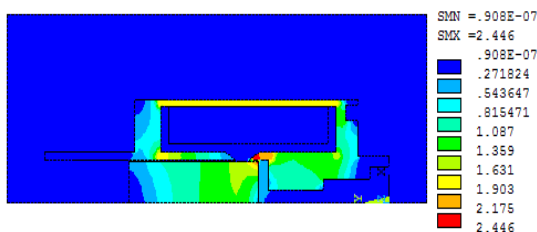


FIG.7 DISTRIBUTION OF MAGNETIC FLUX DENSITY

Optimal Design

The materials used in the plunger and the core for improving the PS are listed in Table 1. Simulations are

performed using ANSYS for these materials. Different conditions for simulating the magnetic force-displacement characteristics of the mentioned materials are presented in Table 2. In FEA, the general premised assumption is that the permeability of the elements in the mesh - although varying from one element to another element - is constant within each single element. The non-linear B-H curves of different used materials are shown in Fig. 8. The referred numbers in this figure are the same numbers of the first column of Table 1. The referred numbers in Fig. 8 are the same numbers of the first column of Table 2. Fig. 9(a) shows the magnetic force-displacement characteristics for the same used materials in core and plunger and Fig. 9(b) shows these characteristics for the different used materials in core and plunger. As it is illustrated, there is a little difference in the magnetic forces when the pure iron is used as the plunger material and when it is not used. In general, the force-displacement curves for all different conditions of simulation are depicted in Fig. 9 and can be compared with each other. The largest and the least values of the magnetic force in all positions of the plunger are obtained for the simulation number 2 and the simulation number 4, respectively. To achieve the better understanding of magnetic circuit, the distribution of magnetic flux lines of PS in the modified design is shown in Fig. 10.

TABLE 1 DIFFERENT MATERIALS USED IN THE ELECTROMAGNETIC ANALYSIS

Number of materials	Materials used for the core and the plunger
1	1020 low carbon steel
2	Vanadium Permedur
3	M-45 steel
4	416 stainless steel
5	Pure iron

TABLE 2 DIFFERENT CONDITIONS USED IN THE SIMULATIONS

Number of simulation	Conditions of simulation
1	core and plunger materials are material number 1
2	core and plunger materials are material number 2
3	core and plunger materials are material number 3
4	core and plunger materials are material number 4
5	core material is material number 1 and plunger material is material number 5
6	core material is material number 2 and plunger material is material number 5
7	core material is material number 3 and plunger material is material number 5
8	core material is material number 4 and plunger material is material number 1

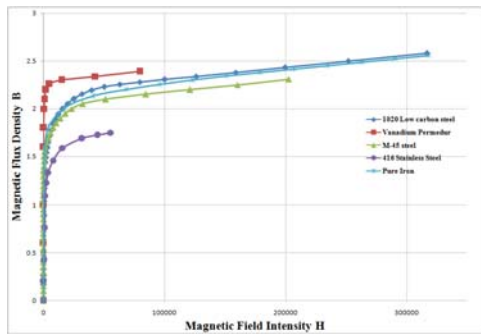
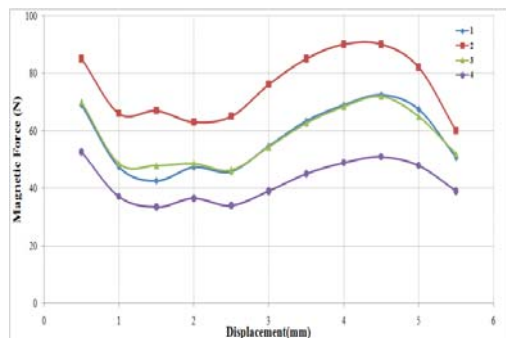
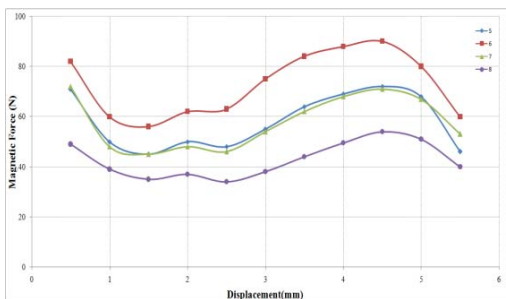


FIG.8 NON-LINEAR B-H CURVES OF THE DIFFERENT MAGNETIC MATERIALS



(A)



(B)

FIG.9 MAGNETIC FORCE VERSUS PLUNGER DISPLACEMENTS FOR DIFFERENT CONDITIONS, (A) THE SAME MATERIALS USED FOR THE CORE AND THE PLUNGER, (B) DIFFERENT MATERIALS USED FOR THE CORE AND THE PLUNGER

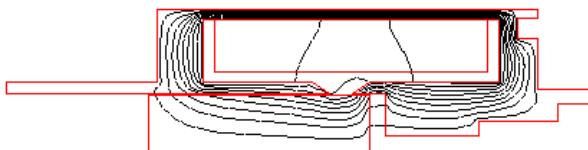


FIG.10 DISTRIBUTION OF THE MAGNETIC FLUX LINES IN MODIFIED DESIGN

Conclusion

In this paper, to improve the performance characteristics of a PS, a FEM program has been developed for analysis of the magnetic field of this type of solenoids. The various soft magnetic materials (1020 low carbon steel, Vanadium Permedur, M-45 steel, 416 stainless steel and pure iron) were utilized as

the core and the plunger materials in the PS to improve the performance of the HCV. Then, the force-displacement curves of the PS for these materials were derived and compared with each other. The simulations showed that the maximum values of the magnetic force are achieved for all positions of the plunger when Vanadium Permedur material is used for both the core and the plunger. In addition, the minimum values of magnetic force were achieved for all positions of the plunger when 416 stainless steel material is used for both the core and the plunger. The experimental results confirmed the validity of the simulation results. Thus, the proposed analysis gave effective guidelines for proper selection of the core and the plunger materials in optimal design of the PS with improved performance. Finally, the distribution of magnetic flux lines in the modified design has been illustrated.

REFERENCES

- Lequence, B. P. "Finite-element analysis of a constant-force solenoid for fluid flow control." *IEEE Transactions on Industry Applications*, 1988, 24(4):574- 581.
- Kano, Y., Maeda, K. "Analysis and reformation of characteristic of linear electromagnetic solenoid." *IEEE Transactions on Magnetics*, 29(1993): 2929-2931.
- Kang, J., Le, J. H., Nah, W. et al. "Radial magnetic field reduction to improve critical current of HTS solenoid." *Physica C*, 372-376(2002): 1368-1372.
- Tao, G et al. "Optimal design of the magnetic field of a high-speed response solenoid valve." *Journal of Materials Processing Technology*, 129(2002):555-558.
- Hong, Y. S., Ha, D. H., Yeom, M. K. "Design of a Two-Dimensional Proportional Solenoid for Miniature Directional Control Pneumatic Valves." *KSME International Journal*, 17(2003): 978-985.
- Angadi, S.V., Jackson, R. L et al. "Reliability and life study of hydraulic solenoid valve. Part 1: A multi- physics finite element model." *Journal of engineering failure Analysis*, 16(2009): 874-887.
- Muller, W., "Comparison of different methods of force calculation." *IEEE Transactions on Magnetics*, 26(1990), 1058-1061.
- Wang, S. M., Miyano, T., Hubbard, M. "Electromagnetic Field Analysis and Dynamic Simulation of a Two-Valve Solenoid Actuator." *IEEE Transactions on Magnetics*, 29(1993): 1741-1746.
- Wu, W., Lovatt, H. C., Watterson, P.A. "Optimum design of a novel solenoid using ANSYS/ Emag." *Proc. English International ANSYS Conf. and Exhibition*, Pittsburgh, USA, 17 - 19(1993): 347 - 350.